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Using trains of femtosecond (fs) laser pulses focused inside the bulk of a dielectric material to produce a permanent modification is a powerful technique. Due to a low heat diffusion coefficient of the matter, the laser energy may be accumulated in the absorption region. The material can be heated to very high temperatures even if the single pulse energy is too low to induce a significant material modification. Then, by adjusting the number of incident laser pulses, it is possible to control the amount of laser energy deposited into the material with a great accuracy.

An intense (TW/cm^2) fs laser pulse focused inside a dielectric material promotes electrons from the valence band (VB) to the conduction band (CB) by photo-ionization processes and the laser energy is absorbed in the near focal-region. At the end of the irradiation process (around hundred fs), the electrons in the CB transfer their energy to the lattice through collisional processes, leading to an increase of the material temperature in the focal volume. Then, this energy is transferred toward the surrounding cold matter through heat diffusion process. The cooling time is of the order of few microseconds for micron-size focal volumes. Therefore, by using a few hundred kilohertz repetition rate, one can achieve pulse-to-pulse accumulation of the temperature.

Due to the different time scales of each processes, one can use a chain of independent models. In this way, all the effects linked to the laser pulse propagation are simulated by a Forward Maxwell code under the paraxial approximation [1], where the Drude model is used to describe the laser energy deposition. The thermal effects are modeled by solving a heat diffusion equation which takes as the initial condition the deposited laser energy and calculates the thermal accumulation [2]. The softening temperature is considered as the threshold for a permanent modification of the matter.

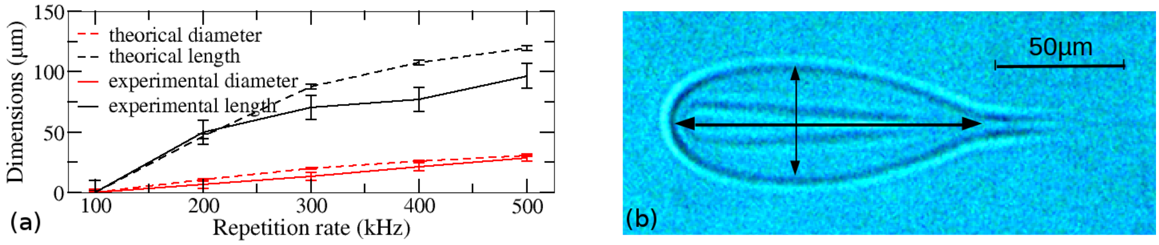

Fig. 1 (a) Theoretically predicted and experimentally observed dimensions of the modified structure induced by a train of 500 laser pulses as a function of the repetition rate (RR). (b) Experimental modification obtained with 500 pulses at 500 kHz and with an energy of 1.3 μJ per pulse and definition of the dimensions under investigation. The laser pulses were shot from left to right.

Simulations were performed for a sodalime glass irradiated by 300 fs pulse trains, at high repetition rates (RR) (>100 kHz). The 1030 nm laser beam was focused by a 10x objective in the glass with an input energy of 1.3 μJ per pulse. The theoretically predicted dimensions of the zone at the softening temperature (dashed line) are compared to experimental measurements (solid line) in Fig. 1(a) with guides for the eyes. We report a threshold-like behavior for the onset of permanent material modifications for RR between 100 and 200 kHz, which is well reproduced by our model. The discrepancy appearing for RR higher than 300 kHz are probably due to the pulse-to-pulse evolution of material properties [3]. Such a temporal coupling between subsequent laser pulses will be investigated in a future work. A typical form of the experimental modifications (RR 500 kHz) is presented in the Fig. 1(b). The "comet-like" shape of the affected area is also observed in our simulations and can be attributed to nonlinear propagation effects and spatio-temporal deformations of the driving pulse.

References

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